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# Performance Analysis of Current Controlled Three Phase Switched Reluctance Motor

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***Abstract*— Switched Reluctance Motor is an old member of Electrical Machines Family.It's simple structures and ruggedness and inexpensive manufacturing capability make it more attractive for industrial application. However these merits are overshadowed by inherent high torque ripple, acoustic noise and difficulty to control. In proposed converter, the hysteresis current control technique is applied for analysis of three phase 6/4 Switched Reluctance motor. Using this technique ,torque, current, and flux linkage speed curves of SRM are obtained at no load and load condition by MATLAB /SIMULINK.**

***Index Terms*— HCC, Switched Reluctance Motor, Converter.**

## I. INTRODUCTION

The inherent simplicity, ruggedness and low cost of a Switched Reluctance Motor (SRM) makes it a viable machine for various general purpose adjustable speeds drive application. The electrical drives play an important role on the productivity to an any industry. The recruitment of drives depends upon the available mains and load characteristics. Brushless variable speed drive using SRM have become popular relative to other drives and represents an economical alternative to Permanent magnet brushless motors in many applications. In last few years the SRM have gain increasing attention since they offer the possibility of electric drives which are mechanically and electrically more rugged than those build up around the conventional AC and DC motors. The primary disadvantage of an SRM is the higher torque ripple compared to conventional machines, which results in acoustic noise and vibration.[1]- [9]

The origin of torque pulsation in an SRM is the highly non linear and discrete nature of torque production mechanism. There are essentially two primary approaches for reducing the torque pulsation. One method is to improve the magnetic design of the motor ,while the other method is to use sophisticated electronic control. Machine designs are able to reduce torque pulsation by changing the stator and rotor pole structures, but only at the expense of motor performance. The electronic approach is based on selecting an optimum combination of the operating parameters, which include the supply voltage, turn on angle, turn off angle, current level and the shaft load. Various converter topologies are analyzed under hysteresis current control.[2]

Over the last two decades different advance control and design strategies have been developed for torque ripple reduction, but due to high torque pulsation those control and design strategies are not effective to reach the acceptable

torque characteristics. Several capacitive converters have been presented in past 20 years[10]-[22].

Passive converter with two capacitor in parallel type[14] active boost capacitor with two series connected capacitor [16]and double dc link converter is presented.[15]

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In this paper hysteresis current control is applied to proposed converter for switched reluctance motor and simulation result is obtained at no load and load condition by MATLAB/SIMULINK.[5-7]

## II. SRM PRINCIPLE OF OPERATION

SRM differ in the number of phases wound on the stator. Each of them has a certain number of suitable combinations of stator and rotor poles. Fig.1 illustrates a typical 3-phase SRM with a six stator /four rotor pole configuration. The rotor of an SRM is said to be at the aligned position with respect to a fixed phase if the current reluctance has the minimum value and the rotor is said to be in the unaligned position with respect to a fixed phase if the current reluctance reaches its maximum value.

The motor is excited by a sequence of current pulses applied at each phase. The individual phases are consequently excited, forcing the motor to rotate. The current pulses must be applied to the respective phase at the exact rotor position relative to the excited phase. When any pair of rotor poles is exactly in line with the stator poles of the selected phase, the phase is said to be in an aligned position; i.e., the rotor in the position of maximum stator inductance.

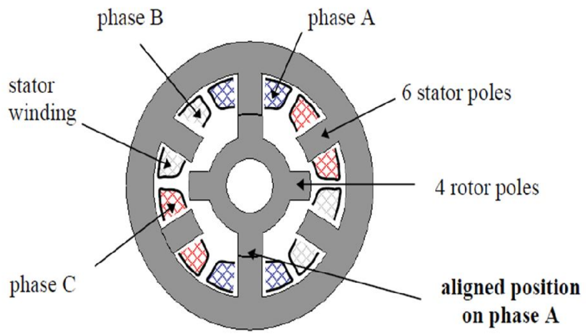


Figure. 1 Three phase 6/4 SRM

The inductance profile of SRM is triangular, with maximum inductance when it is in an aligned position and minimum inductance when unaligned.

## III. CHARACTERISTICS OF SRM CONVERTER

One of the key topics for research in Switched Reluctance Motor drives is the converter topology design. The performance of the Switched Reluctance Motor drive is highly affected by the performance and characteristic of converters. Conventional SRM converters are commercially available, and phase independence and unipolar current are applied widely in industrial applications.[23].Several varieties of converter topologies have been presented in the last 30 years [10]-[12].With continued research, different topologies have emerged presenting reduced numbers of power switches, faster excitation time, faster demagnetization time, high efficiency, high power factor, and high power [24]-[26].In accordance with the operational characteristic of the Switched Reluctance motor, the converter has some basic requirements:

1.Each phase of the Switched Reluctance motor should be able to conduct independently. It means that one phase has at least one switch for motor operation.

2.The converter should be able to demagnetize the phase before it steps into the regenerating region. If the machine is operating as a motor, it should be able to excite the phase before it enters the generating region.

To improve the performance, the converter must satisfy the following additional requirements: (1) allow phase overlap control; (2) utilize the demagnetization energy from the outgoing phase in a useful way either by feeding it back to the source (DC- link capacitor) or by using it in the incoming phase; (3) generate sufficiently high negative voltage for the outgoing phase given a short commutation period in order to reduce demagnetization time;(4) use the freewheel during the chopping period to reduce switching frequency; (5) support high positive excitation voltage for building up a higher phase current, which may improve the output power of motor; (6) acquire resonant circuit in order to apply zero- voltage or zero-current switching, and to reduce switching loss; and(7) apply power factor correction circuit in order to improve the power factor.

## IV. INDUCTANCE PROFILE OF SRM

For a constant phase voltage, the phase current has its maximum value in the position when the inductance begins to increase. This corresponds to the position where the rotor and the stator poles start to overlap. When a phase is turned off, the current flowing in that phase reduces to zero. The phase current present in the region of decreasing inductance generates negative torque. The torque generated by the motor is controlled by the applied phase voltage and the appropriate definition of turn-on and turn-off angles. As is apparent from the description, the SRM requires position feedback for motor phase commutation. In many cases, this requirement is addressed by using position sensors, such as encoders or Hall sensors. The result is that the implementation of mechanical sensors increases costs and decreases system reliability.
When current flows in a phase, the resulting torque tends to move the rotor in a direction that leads to an increase in the inductance. Provided that there is no residual magnetization of steel, the direction of current flow is immaterial and the torque always tries to move the rotor to the position of highest inductance. Positive torque is produced when the phase is switched on while the rotor is moving from the unaligned position to the aligned position.

## V. MATHEMATICAL MODEL OF SRM

The phase voltage of the switched reluctance motor can be written as

$$V = iR + \frac{d\lambda}{dt} \qquad \text{---(1)}$$

Where, V is the bus voltage, 'i' is the instantaneous phase current ,R is the phase winding resistance and $\lambda$ flux linkage in the coil. Ignoring stator resistance, the above equation can be written as

$$P = \frac{d}{dt^2}\left(\frac{1}{2}Li^2\right) + \frac{1}{2}i^2\frac{dL}{d\Theta} * \omega\omega \qquad \text{---(2)}$$

Where, $\omega$ is the rotor speed and $L(\theta)$ is the instantaneous phase resistance.
The power equation can also be written in the form of

$$V = L(\Theta)\frac{di}{dt} + i\frac{dL(\Theta)}{dt} * \omega\omega \qquad \text{---(3)}$$

Where, the first term of the above equation represents the rate of increase in the stored magnetic field energy while the second term is the mechanical output. Thus, the instantaneous torque can be written as

$$T(\Theta, I) = \frac{1}{2}i^2\frac{dL}{d\Theta} \qquad \text{-----(4)}$$

Thus positive torque is produced when the phase is switched on during the rising inductance. Consequently, if the phase is switched on during the period of falling inductance, negative torque will be produced.

## VI. PROPOSED CONVERTER

The proposed converter consists of two discrete switching devices and two freewheeling diodes per phase, as shown in Fig .2.Each phase of converter is the dependent of others, so independent current control can be applied.
The proposed converter has three possible modes of operation. Take one phase into consideration, when both switching device are turned-on, positive magnetizing voltage is applied, and current rises rapidly in the phase winding. If under low-speed operation, phase current will exceed its demanded value fast. At this time, one switch turns off and current circulates through the other switch and one diode. There is no energy transfer between phase winding and dc source. This operation is the so-called freewheeling mode, which applies a low demagnetizing voltage to the phase winding. When both switching device turned off, winding current circulates through two diodes and recharge the capacitor. The demagnetization process is much quicker than freewheeling mode.
The operating modes of an asymmetric converter are shown in Fig. 2.As an independent phase control, the asymmetric converter has three modes. These modes are defined as magnetization, freewheeling, and demagnetization, as shown in Fig. 2(a)–(c), respectively.
Mode1:Magnetizing stage
In this mode,both switches T1and T2 in a phase leg are on,and phase is energized from the supply voltage. The current flow path is Vdc+ -T1-Winding- T2-Vdc -.

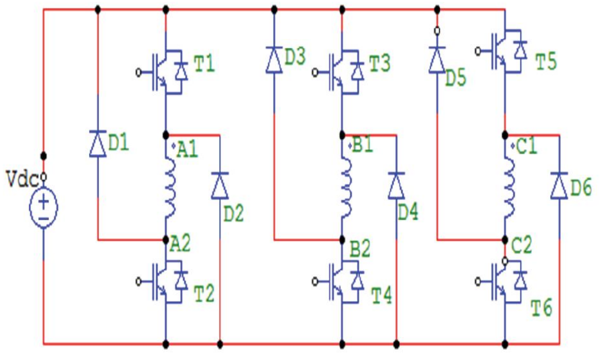


Figure .2 proposed three-phase asymmetric converter

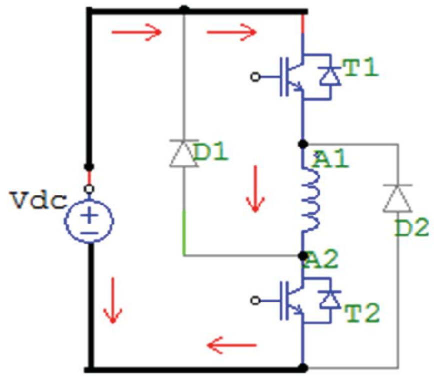


Figure.2.a Magnetization Mode

Mode2:Freewheeling stage

When both switches are off, the freewheeling diodesD1 and D2 allow the exciting current in the coil to keep flowing in the same direction .However the reverse voltage is applied to the excitation coil forces the current to decrease.The current flow path is A2-D1-Vdc+ -Vdc- -D2-A1.

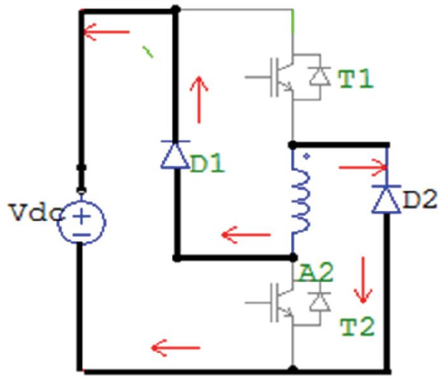


Figure2.b Freewheeling Mode

Mode3: Demagnetizing stage

When any one switch is turned on, the stored energy is dissipated by the phase resistance and the back emf developed in the coil,and thus, the phase current slowly decreases. If the initial current is zero, then the current will remain zero, because there is no voltage applied across the coil.The switches are turned on T2 and turned off T1 to control the desired current level for each phase.

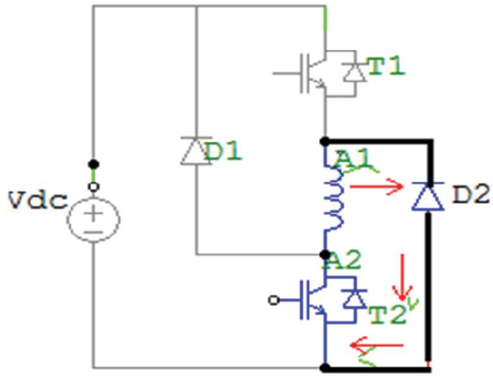


Figure 2.c Demagnetization Mode

V. HYSTERESIS CURRENT CONTROL

Hysteresis current controller maintains a more or less constant current throughout the conduction period in each phase. From Fig.3, the rotor position sensor is connected from the rotor and then the output signal from the rotor position sensor is given as feedback at the base of the transistor T2.From the emitter of T2, the portion of feedback current signal is fed at the input of operational amplifier. The operational amplifier compares reference current signal and phase current.The output signal of the operational amplifier is fed to the base signal of transistor T1.This signal in combination with collector current will flow from the emitter of transistor T1 through phase winding of the motor. The current flow through the phase winding is controlled by turning on and turn off of transistor T1 and T2. The rotor position sensor of switched reluctance motor is simulated and shown in Fig .5.

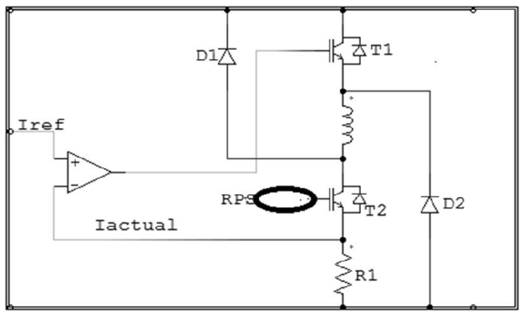


Figure .3 Hysteresis current control

VI. SIMULATION RESULTS & DISCUSSION

In this simulink, a DC supply voltage of 240 V is used. The converter turn-on and turn-off angles are kept constant at 45 deg and 75 deg, respectively, over the speed range. The reference current is 100 A and the hysteresis band is chosen as +-10 A. The SRM is started by applying the step reference to the regulator input. The acceleration rate depends on the load characteristics. To shorten the starting time, a very light load was chosen. Since only the currents are controlled, the motor speed will increase according to the mechanical dynamics of the system. The SRM drive waveforms (phase voltages, magnetic flux, windings currents, motor torque, motor speed) are displayed on the scope. As can be noted, the SRM torque has a very high torque ripple component which is due to the transitions of the currents from one phase to the following one. This torque ripple is a particular characteristic of the SRM and it depends mainly on the converter s turn-on and turn-off angles. In observing the drive's waveforms, we can remark that the SRM operation speed range can be divided into two regions according to the converter operating mode: current-controlled and voltage-fed.

*A. Current-controlled mode*

From stand still up to about 3000 rpm, the motor's emf is low and the current can be regulated to the reference value. In this operation mode, the average value of the developed torque is approximately proportional to the current reference. In addition to the torque ripple due to phase transitions, we note also the torque ripple created by the switching of the hysteresis regulator.This operation mode is also called constant torque operation.

*B. Voltage-fed mode*

For speeds above 3000 rpm, the motor's emf is high and the phase currents cannot attain the reference value imposed by the current regulators.The converter operation changes naturally to voltage-fed mode in which there is no modulation of the power switches. They remain closed during their active periods and the constant DC supply voltage is continuously applied to the phase windings. This results in linear varying flux waveforms as shown on the scope. In voltage-fed mode, the SRM develops its 'natural' characteristic in which the average value of the developed torque is inversely proportional to the motor speed. Since the hysteresis regulator is inactive in this case, only torque ripple due to phase transition.
The proposed converter is simulated by MATLAB/SIMULINK and shown in Fig.4.Torque, current , phase voltage ,speed and flux linkage curves of SRM is obtained at load and no load condition. From the Fig.8 the phase voltage has more spikes at no load condition. When the load increased the voltage spikes has reduced in Fig.12.Fig.9 and Fig.13.shows the current though the phase winding around 100A and it has less distortion. At no load condition, the torque developed by the motor is positive in Fig.10.When the load is applied the negative torque is produced due to back emf in Fig.14.The flux linkage waveform is obtained at different rotor position is shown in Fig.6 . Fig.7 and Fig.15 shows the flux linkage waveform at load and no-load condition. The speed response of switched reluctance motor is obtained around 2700 RPM in Fig .11.

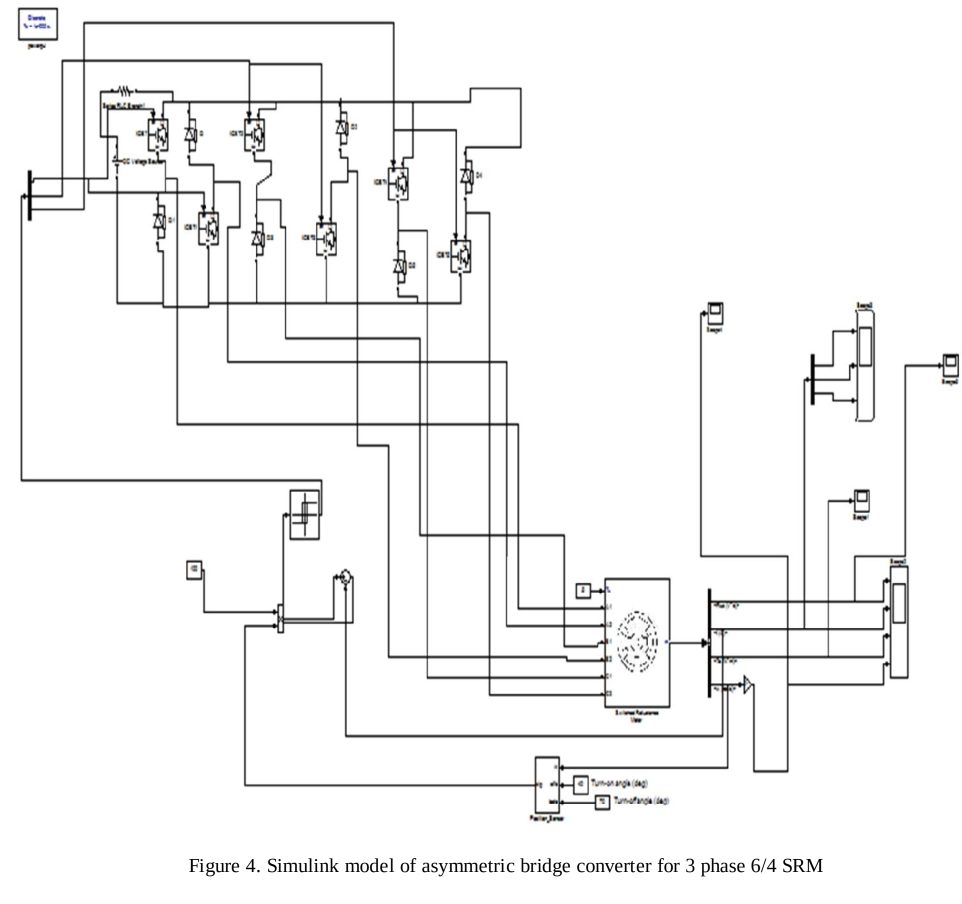

Figure 4. Simulink model of asymmetric bridge converter for 3 phase 6/4 SRM

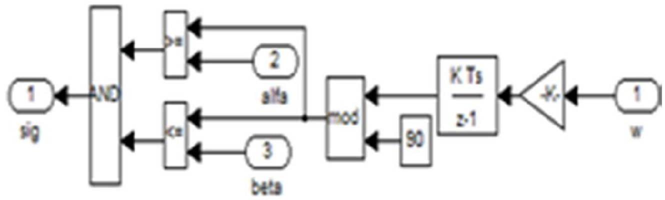


Figure .5 Rotor position Sensor

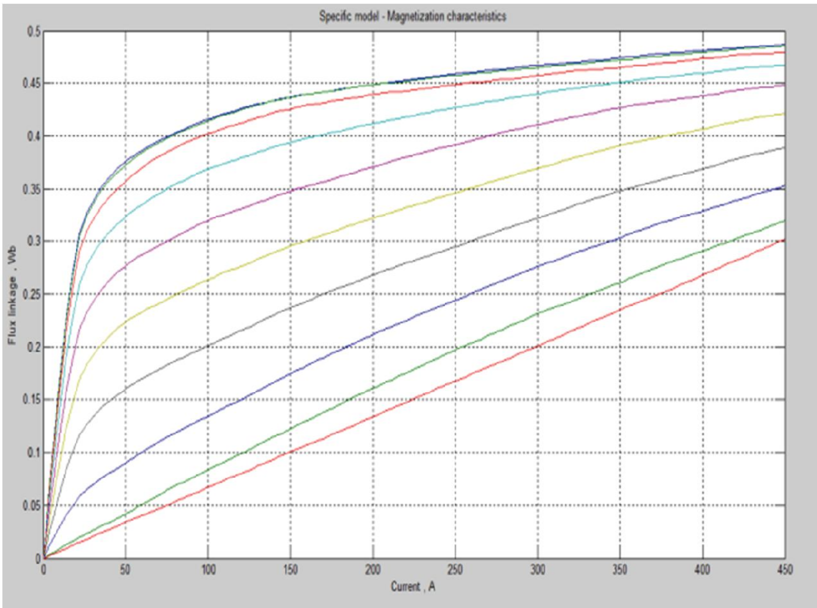


Figure .6 Flux linkage vs. current at different rotor position

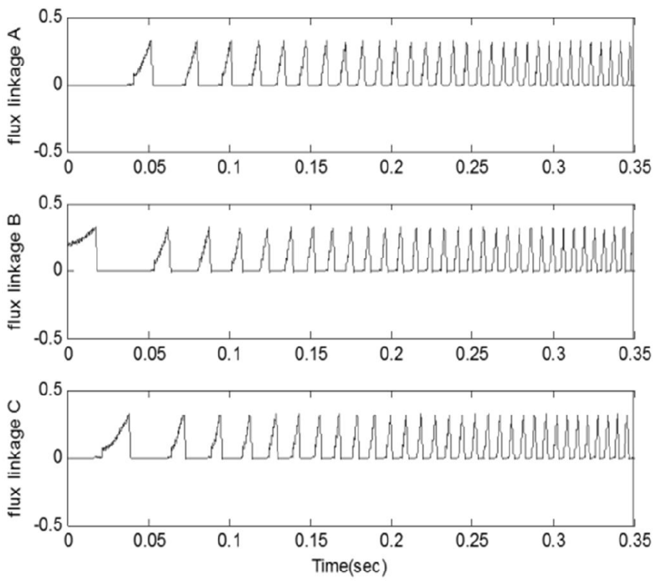


Figure. 7 Flux linkage Vs Time wave form at No load

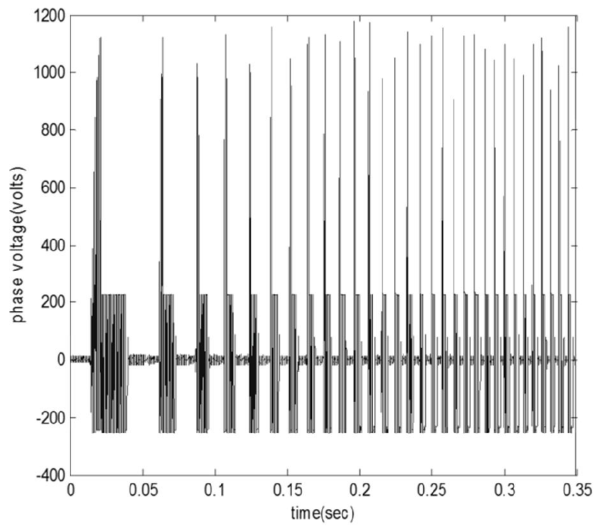


Figure.8 Voltage waveform of phase winding at No load

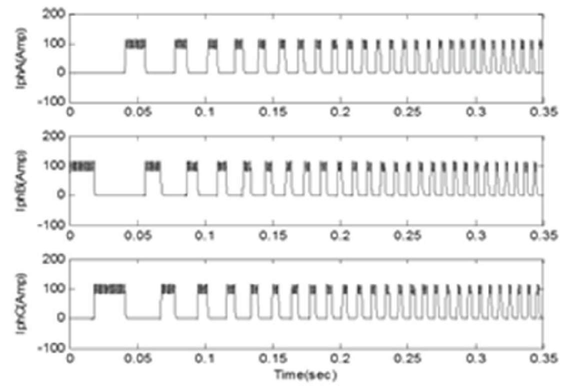


Figure. 9 Current waveform of phase winding at No load

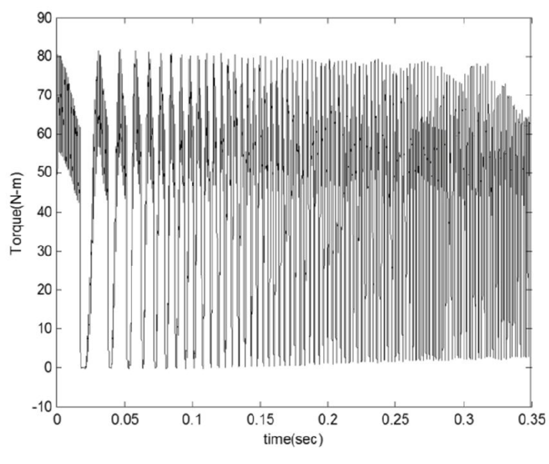


Figure.10 Torque wave form of switched reluctance motor at No load

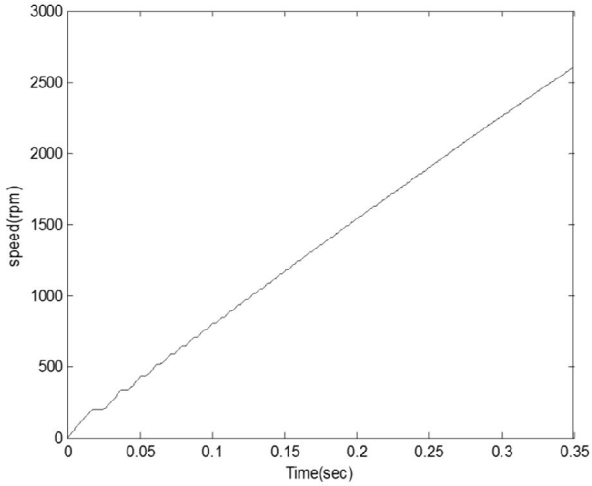


Figure.11 Speed wave form of switched reluctance motor

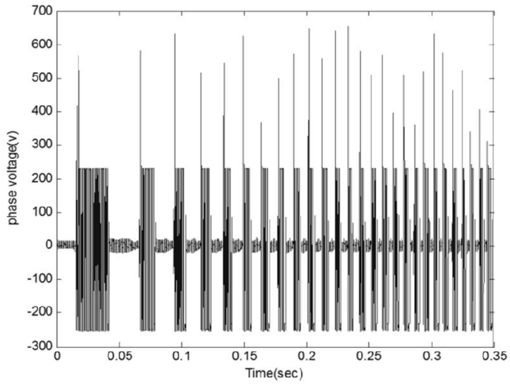


Figure. 12 Voltage waveform of phase winding at load torque 5Nm

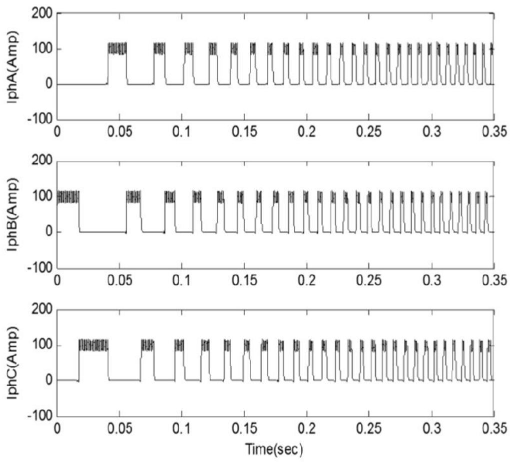


Figure.13 current waveform of phase winding at load torque 5Nm

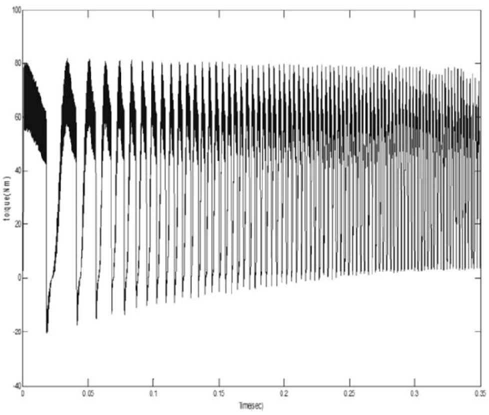

Figure.14 Torque wave form of switched reluctance motor at load torque 5Nm

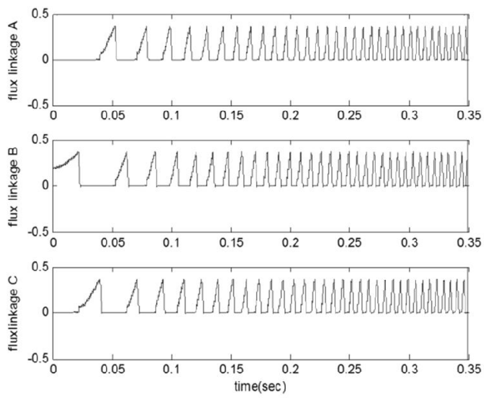


Figure. 15 Flux linkage wave form at load torque 5Nm

## VII. Conclusion

In this paper, the performance of switched reluctance motor is obtained at no load and load condition by proposed converter. From the simulation it is being observed that the torque is developed during change of inductance. For constant inductance (un aligned position) torque developed is zero. To get positive torque, voltage should apply during rising inductance whereas negative torque will develop during falling inductance. The torque pulsation in switched reluctance motor can be minimized by intelligent control like fuzzy, neuro fuzzy, and PSO.

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